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THE REPAIR POLICY DECISION - GUIDELINES WITH COST MODELING TECHNIQUE

RESEARCH REPORT

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ABSTRACT

This paper develops guidelines for repair policy decisions. For a cost-based decision, the technique used in this paper develops a support model from which costs peculiar to each repair policy can be identified and incorporated into a cost equation. The cost equation enumerates the costs which accrue over the life cycle. Statistical methods to determine the significance of cost differences between alternatives are considered. In order that this paper be as widely applicable as possible, a general development of the cost equation was followed to the extent feasible. Thus, a specific cost model could be developed for any repair alternative.

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CHAPTER I

INTRODUCTION TO THE PROBLEM

Technological advances increase the complexity and sophistication of military systems, escalating both the cost of acquisition and the cost of operation. This has alarmed the government, the military, and the taxpayer. Investigation of system procurement criteria emphasizes that acquisition cost must be weighed with system capability and operational cost to arrive at the best system choice. As much as two-thirds of the total "life cycle" cost occurs during the operational life of the system (11).[1] Minimizing costs in this area can realize large dollar savings.

Operational costs include the cost of maintaining a system. This entails large military support organizations which administrate and perform preventive and corrective maintenance actions. In the United States Army, the support organization is broken down to include four levels of maintenance: organizational, direct support, general support, and depot.[2] Briefly, organizational maintenance encompasses tasks performed by the using organization on

1 Numbers in parentheses refer to the list of references at the end of the paper.

2 AR 750-1, Maintenance Concepts.

its own equipment. Direct support maintenance tasks are performed by semimobile units providing close support to active units. Maintenance tasks requiring personnel with higher skill and semifixed facilities are accomplished at the general support level. Depot maintenance provides fixed support for maintenance tasks beyond the capability of other levels, usually in a secure area distant from a combat zone.

The plan for the support of a given system is contained in the support concept which must be systematically formulated during the conceptual or early development phases of a program. The support concept develops concurrently with the operational requirements; each influences the other. The support concept defines requirements covering repair philosophies, maintenance-support levels, personnel factors, and maintenance time constraints. These provide the basis for the establishment of maintainability requirements in system design. For example, if operational conditions dictate that no external support equipment is allowed at the organizational level of maintenance, then the equipment design must incorporate some provision for built-in test.

Failure to integrate the elements of the support concept early in the design and development period increases development time, reduces operational readiness,

and raises the cost of ownership. And in a very real sense, the success of a system's maintainability program in attaining its goals will depend on the extent to which these support requirements have been properly selected, planned, and programmed.

Blanchard and Lowery (2) point out that the first step in formulating the desired support concept is to define a basic repair policy that will best meet the needs of a proposed new system. The repair policy will consider the support to be required at various levels of maintenance. These must be defined from either known or specified data in order to effectively proceed in the development of the basic support concept.

There are a number of possible repair policies applicable to a system design. A system may be designed to be non-maintainable, partially reparable, or fully reparable. A non-maintainable item, usually modular in construction, is a unit which is not repaired when it malfunctions; instead, it is replaced with a new unit. A fully reparable item is a unit which is repaired by the replacement of its individual parts and returned to service. A partially reparable item combines features of both non-maintainable and fully reparable units. Certain assemblies of the unit are designated non-maintainable and replaced as a whole, while other individual parts are also replaced in the re-

pair of the unit.

With complex systems neither non-maintainable nor fully reparable repair policies represent logical design alternatives for the system as a whole. In most instances the system is too costly to replace in one piece and too large to hope to accomplish repair for every individual part within the constraints of operational requirements and economy. Thus partially reparable design will characterize the system concept. However, the type of repair policy which characterizes the lower levels in the hierarchy of the system components must still be reviewed.[3] The decision process is illustrated in Figure 1. Many alternatives may be possible which will meet the system requirements.

The relative value of a system can be described in terms of cost effectiveness. This relates the capability of a system to perform its intended function with the system life cycle cost. If the various alternatives result in systems with equal capability, the alternative with the lowest life cycle cost would yield the most cost effective system and the optimum support concept.

To arrive at this support concept, decisions on design and repair policy must be made at successive design levels from basic part through assembly. Consider an amplifier

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3 In MIL-STD-280, the Department of Defense defines the hierarchy of system levels as system, set, group, unit, assembly, subassembly, part.

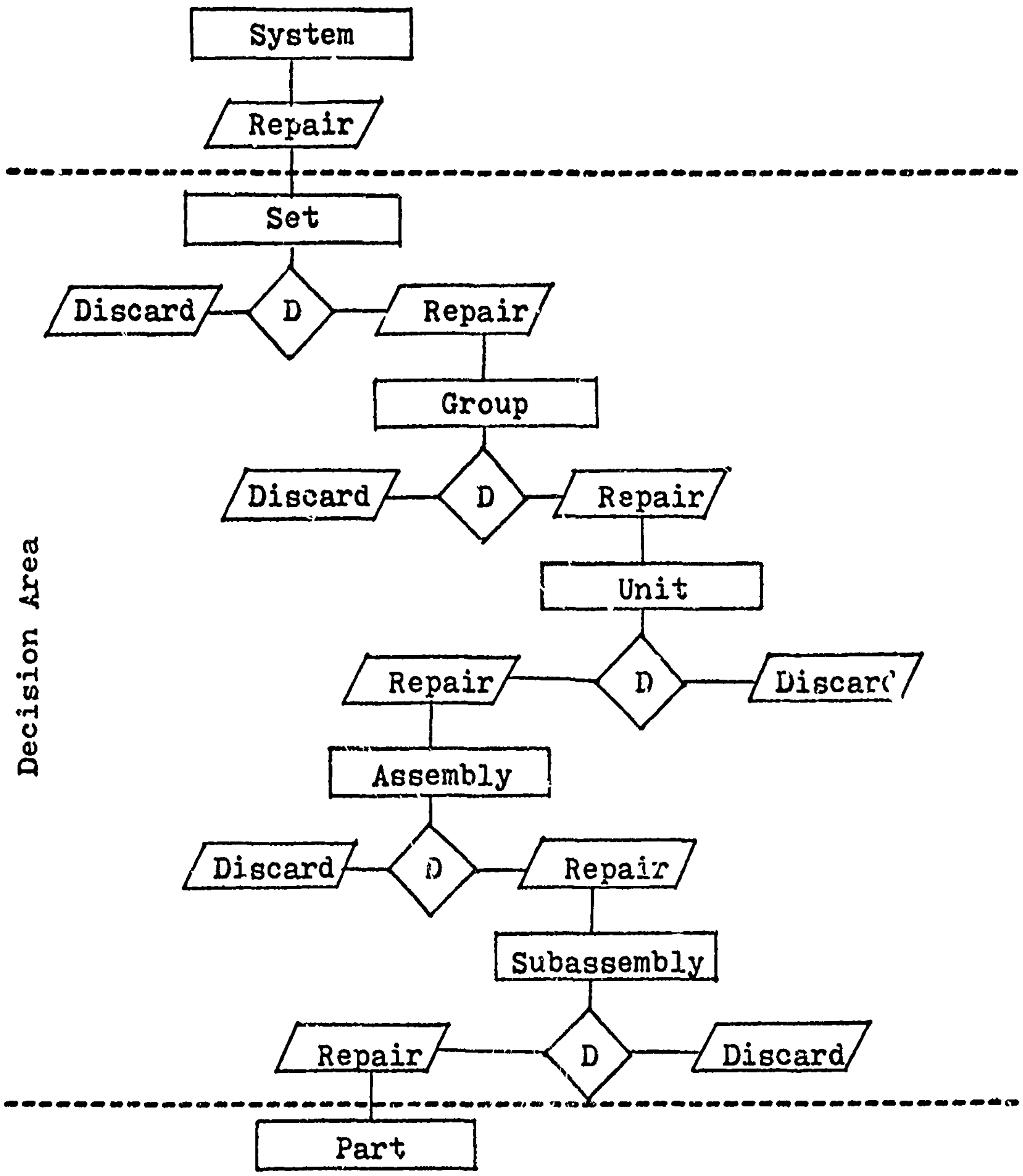

ILLUSTRATION OF THE REPAIR POLICY DECISION PROCESS

Figure 1.

as a component in a unit of a complex electronic system. While possessing the same function and electrical characteristics, it could be constructed of individual parts for full repair; it could be fabricated as a printed circuit board for depot repair; it could be fabricated using an integrated circuit on a plug-in board for non-maintainable repair. These represent several alternatives among many possibilities. The problem is to establish a decision procedure which will yield the optimum support concept. This has previously been identified with minimum life cycle cost. The approach used in this paper is to develop the methodology necessary to construct life cycle cost models.

In Chapter IV, the life cycle cost is subdivided into defined cost elements. The elements comprising the operational cost are defined according to category (accounting, supply, storage, etc.) to be obtainable from present military accounting systems. Should more detailed cost information become available in the future through improved accounting methods, these costs can be further refined. Statistical methods to test the significance of the cost differences between alternatives are discussed in the same chapter; the cost elements are considered as statistical functions rather than fixed quantities and the life cycle cost as an expected cost.

In order that this paper be as widely applicable as

possible, a general development of the cost model was followed to the extent feasible. Thus, a specific cost model could be developed for any repair alternative. However, several basic support models are presented as examples, one of which is solved for the life cycle cost. The example is in the area of electronics, but any type of equipment for which the necessary data is available could theoretically be subjected to the same analysis.

Generally during the early conceptual or proposal phases, reliability and maintainability requirements are imposed on a new system based on military need, as described by the operational requirements, past experience, and similar criteria. An optimum availability requirement is usually determined also. The cost methodology developed in this paper assumes that a functional definition of the system's components has been achieved and that an allocation procedure as discussed by Messer (12) has initially allocated parameters to the functional units achieving the imposed requirements.

Progressing from this point, the evaluation of design-repair policy alternatives requires the definition of additional factors in the support concept to develop the elements of the cost model. These include deployment quantities, test equipment requirements, spare and float levels, initial procurement quantities, and technical

personnel requirements. In this way, the repair alternatives are related to support elements; influences besides cost are brought into consideration, and a total support concept evolves as the repair policy decision is made. This is described in Chapter III. The summary of this work, conclusions, and recommendations for further study are given in Chapter V.

A brief literature survey is discussed in Chapter II, introducing pertinent references to the general area of system effectiveness and support, and particularly to past work in repair policy decision making.

CHAPTER II

LITERATURE REVIEW

General

This chapter reviews some of the available literature dealing with support and maintenance areas, cost estimation, and repair policy decision making. The literature contains a wealth of information on cost breakdowns, cost factors, and repair policy decision models. For the most part, these represent studies conducted under government contract and are oriented toward the specific support organization of the contracting agency. This paper will try to achieve a more general approach. In addition, the cost estimates are considered fixed quantities rather than being treated as statistical functions, an approach suggested in Chapter IV.

The Support Area

It was found that substantial work has been accomplished in the support area pertaining to the repair policy and its implications. This has been incorporated in basic primers in the field of Maintainability (2, 7, 8, 11). Goldman and Slattery (8) also show the correlation between part failure rate, assembly size, and repair policy in determining optimal module design, but the results are

limited to certain types of electronic equipment. Extension of this work is beyond the scope of this paper.

The key role that the repair policy decision plays in leading to the formulation of the complete support concept has not been adequately represented in these references. The discrepancy has probably arisen from a design oriented attitude of the authors, since maintainability is considered an element of design.

The Repair Policy and Cost Models

At this point, a brief description of some of the existing repair policy modeling techniques will help to establish a background for the development of this paper. The first efforts at cost reduction in the repair decision area took place in the late 1950's. Rizer et al (15) constructed two simple operational cost equations for Air Force equipment already in the field. The model compares the cost of depot repair with the cost of base level condemnation and replacement. The authors noted the difficulty of obtaining cost data, recommending standardized cost elements throughout the Department of Defense and a study to determine cost variance.

Andrea (1) evaluated module replacement and "disposal at failure" maintenance on a particular Air Force ground electronic communication equipment. The yearly

maintenance cost was formulated for the existing equipment based on actual cost studies and compared to a proposed modular design with costs estimated in relation to those of the existing equipment. The author concluded from the study that substantial savings could be obtained with the use of disposal at failure maintenance. However, Stone et al, (16) in a similar study of tube type equipment found that within the range of optimum module size, there was little cost difference between expendable and reparable design. The major desirability of expendable design over repair was found to be in the areas of downtime and manpower requirements, but supply-line capability becomes more critical.

Similar to the above works but of later vintage are studies by Wreiden (18), Purvis (14), Davis (6), Tempo/GE (8), and the Institute of Logistic Management (5). The Wreiden model is basically a linear cost prediction model with failure and repair rates as independent variables. The model neglects acquisition costs which vary significantly with design alternatives. A revision of the model was accomplished by Purvis (14) for the U. S. Air Force with intended application during the development phase. Detailed cost breakdown requirements and computer solution at each decision choice make this an unattractive model.

Pursuing a parrallel course. Todaro (17), considers a dynamic programming approach for determining repair or replace maintenance policies and optimum module size for equipment with design commonality. The repair rate was assumed constant and the problem treated a fixed design. Extensive development along these lines was accomplished by Bluel (3). In his work, a dynamic programming formulation is presented which provides the optimum replace versus repair decision for a specific hierarchical configuration. Assumptions include negative exponential times-to-failure and times-to-repair. This strictly analytic treatment considers the cost function a constant and neglects the support environment unless it can be resolved as an analytic set of restrictions.

Several additional works have been found which deal with aspects of cost analysis considered pertinent to the work carried out in this paper. Although of interest, they do not attempt to solve the repair policy decision problem. Large (10) treats the problem of estimating major equipment costs considering data adjustment, price level changes, and statistics. Harkins and Shemanski (9) consider data adjustment, present worth factors, and regression in developing a historical cost basis.

In summarizing this chapter it is obvious that considerable work has been carried out in the field of

repair policy decisions. However, the limited applicability of each paper has made them little more than paper presentations of particular cases. Treating the costs as constants with no consideration of variability also casts a doubtful shadow on unconditionally accepting one repair policy over another. There may be no valid statistical reason for making a decision on cost alone. Therefore, this paper attacks the repair policy decision with a general treatment of the guidelines and modeling techniques. Applications of statistics to the decision are also considered.

In Chapter III, the influences which affect the repair policy decision are considered. Also treated is the evolution of the total support concept through repair policy decisions.

CHAPTER III

BASIC DEVELOPMENT OF THE SUPPORT CONCEPT

General

With the conceptual development of a new or improved operating system, the planning and organizing groups usually establish basic guidelines as to the system's characteristics of operation. The mission or job that is to be performed is described in as much detail as possible, and acceptable methods for attacking the job are discussed. Primary among the concerns of these groups are the consequences or price of failure to adequately perform the mission. Thus, it becomes necessary to ensure that a system is capable of performing properly a large percentage of the times it is called on to operate. This aspect of system operating characteristics is termed availability, which is a function of the reliability and maintainability of that system. Availability can be concisely defined in terms of the system mean-time-between-failures and mean-time-to-repair.

From the mission profile and system operational requirements, a functional design of the system takes form. Major system building blocks - set, group, unit, assembly - are structured, and their corresponding functions are defined in terms of system requirements. To meet the

functional block design, existing or new hardware designs are proposed, and an initial allocation procedure takes place which allocates maintainability and reliability parameters to the functional blocks while meeting the desired system availability. Within the constraint of allocated parameters, acceptable designs are selected by cost analysis.

Support Criteria

Up to this point nothing has been mentioned concerning support. However, the basic development of the support concept takes place concurrently with the preceeding design and allocation procedures. The system operational requirements are initially defined through a feasibility study of the proposed mission profile. Besides the quantitative requirements of availability, maintainability, and reliability, several factors are defined which impact the support concept providing constraints on proposed designs:

1. A definition of system deployment requirements. Such data cover quantities of installations or field commands, number of systems per installation or command including reserve systems to meet availability requirements, sparing levels, location of installations and commands to establish supply criteria, distances from fixed support

facilities, and operational environment of each unit of the system.

2. A definition of system-utilization requirements to include the system operational cycle, operational time per cycle for peacetime requirements, and operational time per cycle for combat conditions.

3. An identification of system constraints covering specific operational limits. The skill level of the system operators and the technical competence of the maintenance force at each level of maintenance as well as their number must be considered. The available tools, test equipment, testing methods, and repair facilities must be compared to the requirements of proposed designs.

The Support Concept

With the various support factors defined and hardware designs developed, a number of repair policies, each reflecting particular design, can be enumerated at each level of the system. The support factors combined with the physical hardware configuration vitally influence the amount of time required to repair a fault in the system and its cost of ownership. This necessitates a unified effort by the design and support personnel to develope a feasible system which has the capability of being supported in a military environment as well as being

capable of operating in a required manner from a design standpoint.

Since a repair policy relates a design to the support factors, a support concept is achieved. The repair policy and design define the support requirements. As decisions are reached throughout the levels of the system, the repair policies with their support requirements define the system support concept.

The question arises as to how the choice of repair policy is made among several alternatives. As intimated in the preceeding paragraphs, the initial concern involves the feasibility of design and support. Once the alternatives are found to be feasible, the function of a good development group is to meet the requirements at the lowest cost. Thus the cost of each alternative over the anticipated life of the system must be estimated for comparison. Cases may arise where no significant cost difference exists between alternatives and the decision criteria become less quantifiable. There are several factors of major importance to be considered in such cases:

1. At this point it is assumed that each alternative at least meetsthe allocated availability requirements. However, it is also possible that an alternative will exceed these requirements, giving better performance

characteristics. The higher availability of one portion of the system may balance another portion where the operational availability fails to meet the requirements as predicted.

2. A high technical skill level among military personnel is difficult to maintain, and specialized support requirements complicate repair. Standardization of items and their support lends itself to a combat environment.

3. One repair policy may have more desirable characteristics for a given system. Some examples are as follows:

A. When non-maintainable design is chosen over reparable design, the burden on repair requirements is lightened. The need for highly trained technicians, maintenance equipment and repair facilities is reduced. However, storage facilities, spare requirements and channels of supply become more critical.

B. Since a non-maintainable design requires no accessability within the item, the size and weight may be reduced, and the item encapsulated or sealed. The result is a smaller package with increased reliability. The improvement in reliability results from the encapsulation and the fact that it is free from repair. In contrast, improper handling and part degradation in the repair process often result in a repaired item having a lower reliability. In other words, the item is not returned to a

"like new" condition. A non-maintainable design usually requires more connectors (pins, plugs, etc.) than a reparable design. In environments where vibration and humidity are prevalent, weakening and corrosion of the connectors may degrade the reliability of the design.

C. When a non-maintainable design fails and is thrown away, reliability information is lost. The trouble shooting of the component parts which occurs in reparable designs usually identifies the cause of failure within the failed item. This loss of failure data poses no problem as long as an item with a non-maintainable design performs as predicted. However, if in actual use the item failure rate does not correspond to its predicted value, a sampling plan and analysis of failed items may have to be inaugurated to determine the failure mechanisms and methods to improve performance.

D. A non-maintainable design will probably result in a lower cost per item. Development and manufacturing costs are reduced because of the elimination of accessability requirements. However, this minimizes any disposal value of non-maintained items. The production quantities are also larger, reducing cost per unit. Of course, this does not imply lower life cycle cost.

E. In large electronic systems, automatic built-in test equipment is extensively used for fault detection

and isolation. The fault is isolated to a unit or module which is replaced. The failed item is frequently sent to a depot or other major repair facility to be repaired rather than be repaired at the site. Non-maintainable designs are quite compatible with this method of testing, since the unit or item is the lowest level which is tested at the site.

In Chapter IV, particular life cycle cost elements are discussed and a general cost equation developed to evaluate the repair policy decision from a cost standpoint. Cost variances are also considered. The methods of solution used in Chapter IV will offer guidelines for cost modeling techniques that could be applied to any support model.

CHAPTER IV

COST-BASED SOLUTION OF THE REPAIR POLICY DECISION PROBLEM

Introduction

In this chapter, cost considerations associated with life cycle cost are discussed, and specific cost functions representing the cost elements of the support model are considered in the formulation of a cost equation. The cost equation yields a total cost which is the expected life cycle cost based on the predicted system life. Statistical methods are outlined to compare the expected costs between the design-support alternatives under consideration. Obviously, each system application, type of hardware, environment, and repair policy can present a unique support concept, so a multitude of support models could be studied. Several models are presented. However, it seemed more appropriate to follow through with one complete example since this solution could be used as a guide for any particular problem to which the assumptions in this paper apply.

Cost Considerations and Support Models

The overall objective in a cost-based repair policy decision process should be to identify at each decision point the design-support alternative which minimizes the

costs of owning a system. This requires enumeration of the costs which would be accrued / the alternatives throughout the system life cycle. However, knowledge of these costs is needed in the design stage - often before any physical hardware exists - since it is at this time that decisions are made. Therefore the costs are predicted. The sources of this data are the user's cost history of similar items and their support, the contractor's cost history of similar items, and the contractor's cost estimates based on development reports.

Caution must be exercised in the use of historical cost data. The costs must adequately represent the alternative under consideration. They must also be current. That is, the data must have been accumulated rather recently over a short period of time to eliminate bias from increased cost of labor and materials and other inflationary effects. Such data is not usually available in sufficient quantity, and data accumulated over several years can be used provided it is transformed by some inflation factor into a current cost. A good data collection system is needed which collects both time and cost information for each data point. What has been said about data collected in the past can also be applied to the future operational costs to be predicted. Costs expended in the future must include the effects of inflation and be

discounted to a present cost.

In general, life cycle costs can be broken down into three areas: acquisition, operational, and disposal costs. From the repair policy, support concept, and the support factors which were defined in the feasibility study, a support model can be developed for each alternative. From this model operational (support) cost elements can be identified which account for the toatl operational cost. The acquisition cost is composed of the procurement cost and the allocated installation cost, if any; the procurement cost accounts for the design, development, and manufacture of the item. The disposal cost accounts for any planned disposal action on the item as well as any salvage value it may have from the resale of its component materials.

How these costs are defined and subdivided into more detailed costs is a matter of personal discretion. But, unless there is some correspondence between the defined costs and the data elements obtained from a data collection system, it may be impossible to obtain a true life cycle cost estimate. Such a life cycle cost estimate takes into account the total cost even when there are cost elements common to each alternative. Only in this way can the true magnitude of the cost difference between alternatives be assessed.

Several support examples are now presented to clarify

the preceding paragraphs, and to show the contents of a support model. Some assumptions have been made which simplify the presentation of these models. This does not weaken the approach used in this paper. Additional factors can be introduced which further enhance the model.

Assumptions implicitly made include:

1. Physically damaged items from combat or misuse are not considered in the support models; that is, failures are due to chance and wearout.

2. Items from supply lines meet specifications.

3. Tests and diagnoses are perfect. Failed items have definitely failed and do not meet specifications.

4. Repaired items meet specifications. Degradation resulting from the repair process can be accounted for in a derated time to failure.

5. The supply line and sparing policy provide adequate spares and parts required for repairs.

To simplify the presentation, each of the following examples considers only two alternatives. The procedure, however, can handle any number.

Example 1. A new Army jeep is being developed. Under consideration are two engines and their support plans. One idea is to incorporate the engine and support plan currently in use for existing jeeps into the new design. The existing plan calls for the jeep to be shipped to certain

general support shops when there is a malfunction within the engine block. At the shop, a preliminary diagnosis is made. Certain minor repairs are handled there, and the jeep is, if possible, returned to service. Major repairs require shipment of the engine to a depot in the continental United States for overhaul. After overhaul, the engine is returned to general support.

Another engine of new design can also be used. Because it encompasses major engineering changes, it is decided to equip one depot in the United States with the capability to do overhaul work on the block. This plan calls for the jeep to be shipped to certain general support shops when there is a malfunction within the engine block. Then the block is removed and shipped to the depot designated for the overhaul of this engine on a direct exchange basis. After the engine has been repaired, it is placed in the Army supply system.

Note the difference in the support plans. The new engine requires more specialized repair. However, because of the overhaul and exchange policy, fewer spare parts, engines, and float jeeps have to be kept in the area of operation. This is accomplished by stretching the supply line. Although the engine requires specialized repair, the maintenance burden in the area of operation is reduced by the consolidation of repair facilities. Figures 2 and

3 show proposed support diagrams for these alternatives.

Example 2. A compact digital field computer is being developed to replace an older version now in use which is a solid state device but of piece part design. The new computer is to incorporate more recent solid state developments including printed circuitry and integrated circuits. A typical function of the device would be to calculate coordinates and firing information for an artillary unit. The logical section of the computer consists of several similar circuits each physically composed of piece parts and integrated circuits. Two feasible alternatives are contemplated. One is to mount piece parts and integrated circuits for each circuit on a plug-in printed circuit board. When a board fails it is to be replaced and returned to a central storage point where it will be sent in lots to a contractor for repair. The other alternative is to make two boards for each logic circuit. One board will contain the piece parts and will be discarded on failure. Integrated circuits are mounted on the other. When a failure is indicated on this board, it will be replaced. The failed board will be returned to a depot where the bad integrated circuit will be isolated and replaced. The board will then be placed in the supply system.

In the first case, the personnel skill level and

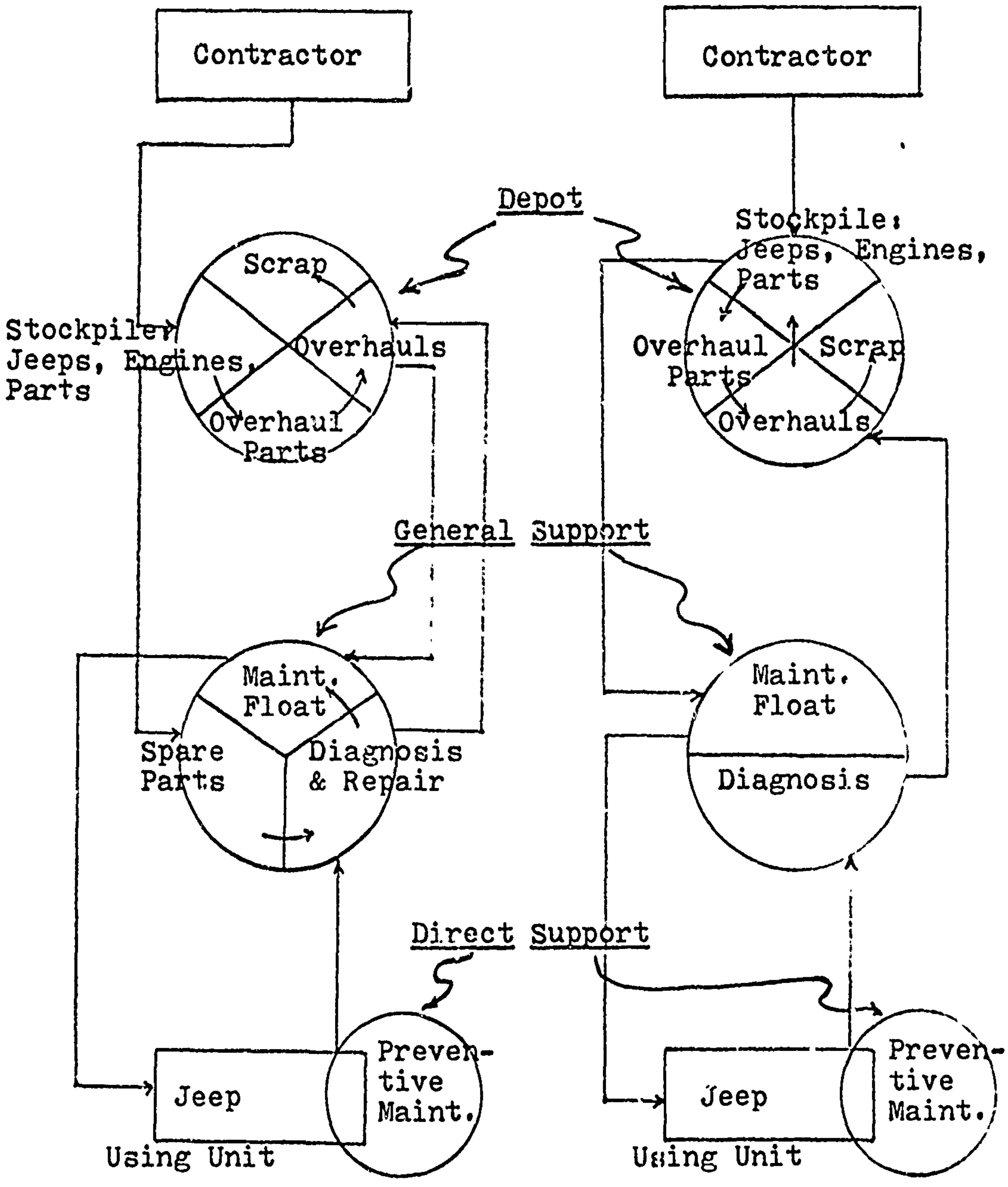

Figure 1.

EXISTING JEEP ENGINE

Figure 2.

NEW JEEP ENGINE

SUPPORT DIAGRAMS FOR JEEP
ENGINES AS DESCRIBED IN EXAMPLE 1

specialized equipment necessitate an outside source for the repair. This may result in higher repair cost, but the maintenance burden is lightened. The second case considers an alternative to contractor repair, but production costs may be increased due to the increased number of boards and connectors. Here it is assumed that the piece parts are less costly and less reliable than the integrated circuits. This conclusion can not be accepted with blind faith in advanced technology. Figures 4 and 5 show proposed support diagrams for these alternatives.

Example 3. In the development of a new space communications network, there are several design and support alternatives applicable to the equipment which will comprise the fixed ground installations. A design group is now working on a multistage amplifier section for one type of receiver. The designs being considered are expected to be highly reliable with the biggest concern being wearout failure as certain components drift out of tolerance. Direct support of the fixed ground equipment will be accomplished with skilled technicians and equipment. One alternative envisions piece part construction. When the amplifier fails the faulty part will be isolated and replaced. When the amplifier drifts out of tolerance a group of key components will be replaced. Since there will be other communication channels a standby receiver is

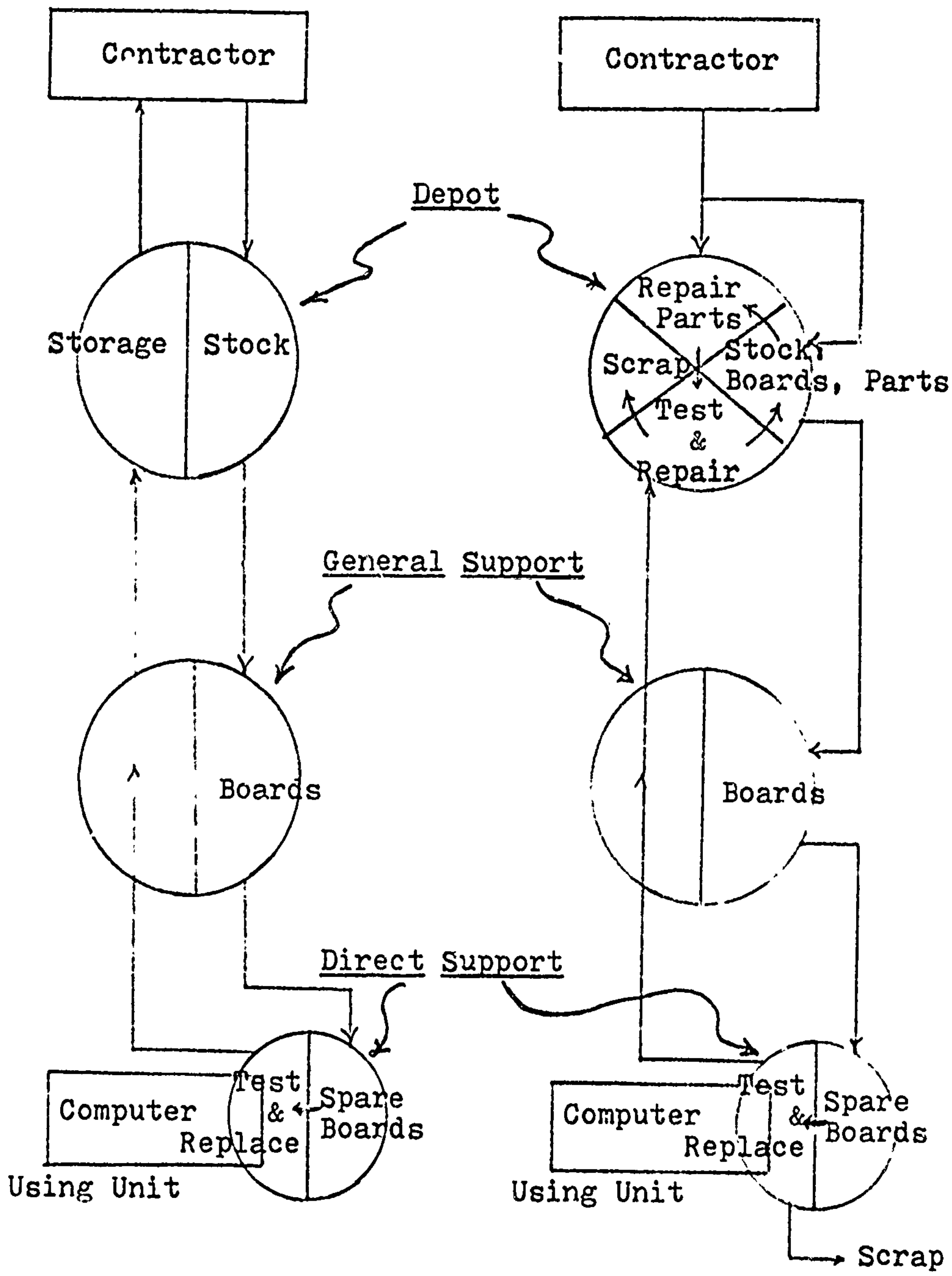

Figure 4.

Figure 5.

SUPPORT DIAGRAMS FOR COMPUTER
LOGIC AS DESCRIBED IN EXAMPLE 2

not contemplated. However, there will ɔ auxilliary installations. The other alternative is to design the amplifier section as a plug-in board to be discarded at failure. Figures 6 and 7 show the proposed support diagrams. Note that because of the fixed installations, maintenance at general support will not be required.

Defining Costs, Cost Factors, and the Cost Equation

Until now the problem of identifying cost elements and factors has been treated in general. In this section acquisition, operational, and disposal costs will be subdivided and defined along with other factors necessary for the calculation of the life cycle cost equations for the models covered in this chapter. It must be realized that other costs and support factors could be defined as the ne arises. The basic attempt here is to show the technique necessary in formulating a cost equation which adequately encompasses the life cycle cost.

The following are definitions to be used in formulating a general cost equation. The definitions are divided into two parts: definitions of the input data necessary for the model, and supplementary definitions involving combinations of the input data which result from the application of the equations which follow. It is assumed that the input cost data has been treated as indicated in the

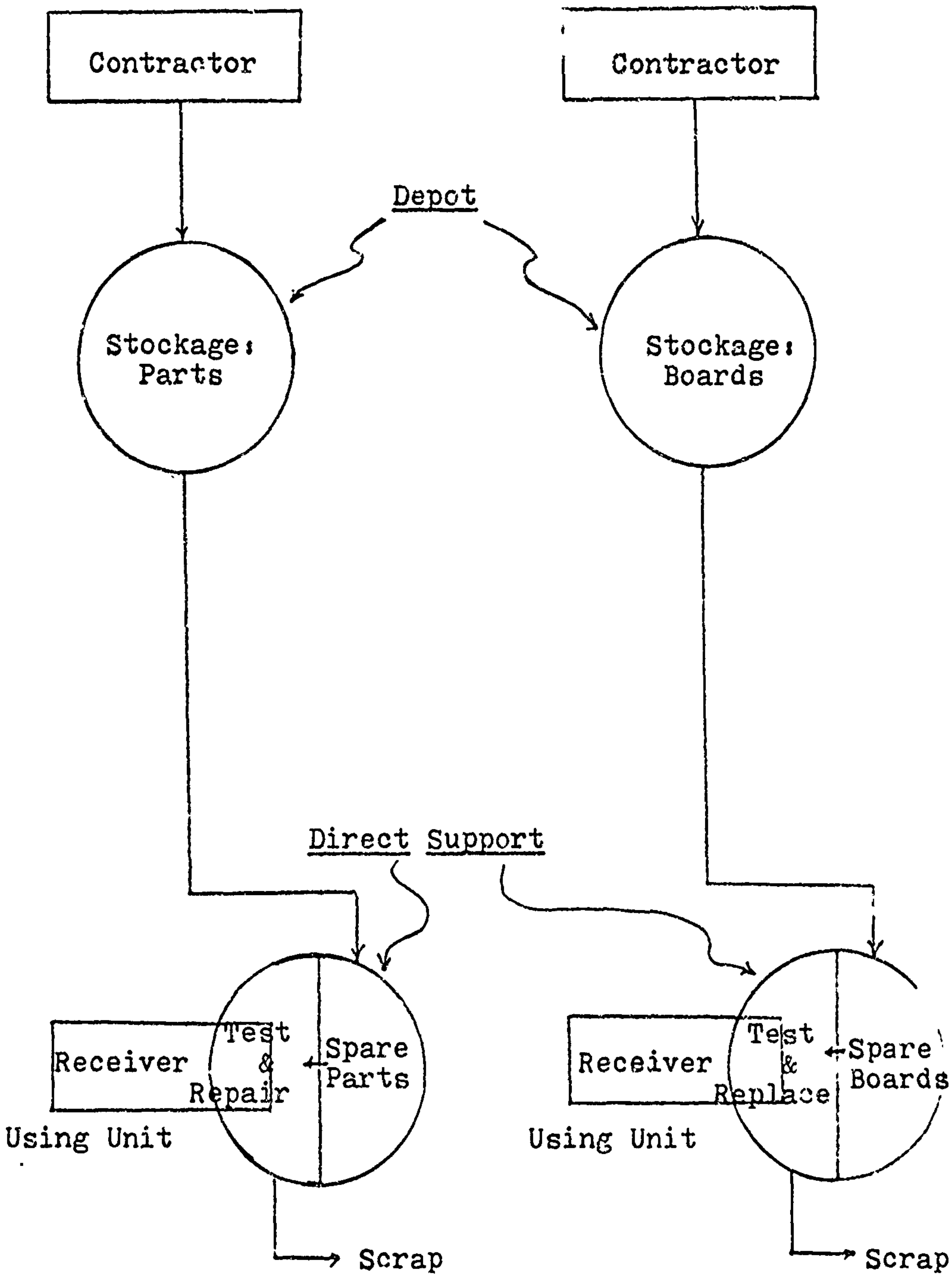

Figure 6.   Figure 7.

SUPPORT DIAGRAMS FOR RECEIVER
AMPLIFIER AS DESCRIBED IN EXAMPLE 3

previous section; that is, inflationary effects have been eliminated from historical data and included in future costs. Also, future costs have been discounted to a present cost. Specific cost assumptions will be included in the definitions.

Input data definitions:

CAC Federal Stock Accounting Cost - the cost of maintaining accounting, stockage, and demand records for an item or part on a yearly basis. Assumed the same for all parts and physically distinguishable items. The cost does not include parts and items already being accounted.

CHCM Corrective Maintenance Manhour Cost - the cost of a corrective maintenance manhour, including personnel and use of existing maintenance facilities. Assumed the same for all levels of maintenance.

CD Disposal Cost - The cost of planned disposal action on an item accrued over the system life.

CDOC Documention Cost - the cost of technical manuals, parts manuals, and provisioning documentation for the item.

CEQ Equipment Cost - the cost of additional or specialized equipment, tools, and facilities used in the support of the item.

CFAB Fabrication Cost - the cost of additional procurement of the item after initial acquisition. Expressed as a cost per item.

CFSN Federal Stock Number Cost - the initial cost of adding a new item or part to the Federal Stock System.

CI Installation Cost - the cost of installing the item as part of a system in an operationally ready mode. Expressed as a cost per item. If there is no contractor cost of installation, the military set up cost is considered unaccountable here.

CM — Manufacture Cost - the cost of design, development, fabrication of the initial procurement quantity. Expressed as a cost per item.

CHPM — Preventive Maintenance Manhour Cost - the cost of a preventive maintenance manhour including personnel and use of existing facilities. Assumed the same for all levels of maintenance.

CS — Salvage Worth - the net salvage value of a failed item for either reparable or non-maintainable design. It is assumed that parts have no salvage value.

CSP_i — Spare Part Cost - the cost of additional purchase of a spare part after initial acquisition where the subscript identifies the specific part type. Expressed as a cost per part. No shortage penalty cost is considered.

$CSPI_i$ — Initial Spare Part Cost - the initial cost of a spare part during acquisition where the subscript identifies the specific part type. Expressed as a cost per part.

CST — Storage Cost - the yearly cost of storing spare items or parts in the Federal Stock System. For physically small parts and items, the cost is assumed equal and independent of quantity. Therefore, parts and items already in the system are not included.

CSUP — Supply Line Cost - the yearly cost of maintaining channels of supply for an item or part. For physically small items and parts, the cost is assumed equal. Costs are not distance based.

CT — Training Cost - the yearly cost of maintaining a specified number and skill level of maintenance personnel for the item.

CTI — Initial Training Cost - the cost of the initial training program to provide a specified level of technical support for the item.

MTBF — Mean Time Between Failure - the mean of the times to failure distribution of the item over its operating life. No specific distributional form is assumed. The MTBF is expressed in hours.

MCT	Mean Active Corrective Maintenance Time - the expected time to perform corrective maintenance actions: to effectively repair an item and return it to a servicable condition, or to replace a non-maintainable item. Expressed in the form of maintenance manhours. No specific distribution is assumed.
MPT	Mean Active Preventive Maintenance Time - the expected time to perform preventive maintenance actions on an item. Expressed in the form of maintenance manhours. No specific distribution is assumed
NC	The number of new classifications in the Federal System. It includes both the item and its component parts.
NE	The initial number of items in float equipment and spares stockage.
NFAB	The number of items procured after initial acquisition.
NI	The number of items per system.
NS	The expected number of items to be salvaged over the system life
NSP_i	The procurement quantity of a spare part purchased after initial acquisition where the subscript identifies the specific part type.
$NSPI_i$	The initial procurement quantity of a spare part where the subscript identifies the specific part type.
NST	The number of standby systems deployed in support of active systems.
NSYS	The number of active systems initially deployed.
NT	The initial procurement quantity of items.
OS	The expected system operating time expressed in hours per day. It is assumed that the item and its parts operate when the system operates.
P	The preventive maintenance cycle expressed as the number of operating hours per preventive main-

tenance action.

T The expected system life in years.

Supplementary definitions:

CAQ Acquisition Cost - the cost of acquiring the item as part of a system in an operationally ready mode.

CCM Corrective Maintenance Cost - the cost of repairing failed items over the life of the system for the reparable item. For the non-maintainable item, it is the cost of replacing the item. In neither case is the cost of spares included.

CDT Total Disposal Cost - the cost associated with failed items and phase-out.

CLC Life Cycle Cost - the total cost of an item accrued over the system life.

COP Operational Cost - the total operational cost of the item.

CPI Phase-in Cost - the combined cost of installation, equipment, and initial training for the item.

CP Procurement Cost - the combined cost of manufacture, documentation, initial spares, and initial federal stockage.

CPM Preventive Maintenance Cost - the cost of preventive maintenance on an item over the life of the system. Assumed to be a function of the system operating cycle.

The acquisition cost of an item is the sum of the procurement cost and phase-in cost,

$$CAQ = CP + CPI \quad . \tag{1}$$

The procurement cost combines the costs of manufacture of the initial item procurement quantity, documentation, initial spare procurement quantities in the case of reparable items, and initial Federal Stock entry of new

items and parts,

$$CP = (NT)(CM) + CDOC + (NC)(CFSN) + \sum_i (NSPI_i)(CSPI_i) \quad . \quad (2)$$

The phase-in cost consists of the costs of maintenance facilities, equipment, and initial training,

$$CPI = CEQ + (NI)(NST + NSYS)(CI) + CTI \quad . \quad (3)$$

The substitution of Equations 2 and 3 into Equation 1 will yield an expression for the acquisition cost.

The operational cost of an item is the sum of maintenance, training, supply, stockage, and added materials over the life of the system. When the corrective maintenance cost is expressed as

$$CCM = \frac{365(NSYS)(OS)(T)(MCT)(CHCM)}{MTBF} \quad (4)$$

and the preventive maintenance cost is expressed as

$$CPM = \frac{365(NSYS)(OS)(T)(MPT)(CHPM)}{P} \quad , \quad (5)$$

the operational cost can be written in the form

$$COP = CCM + CPM + (NC)(CAC + CST + CSUP)(T) + (CT)(T)$$
$$+ (NFAB)(CFAB) + \sum_i (NSP_i)(CSP_i) \quad . \quad (6)$$

The total disposal cost is the difference between the disposal cost and salvage worth and will be expressed as

$$CDT = CD - (NS)(CS) \quad . \quad (7)$$

The life cycle cost is the sum of the acquisition, operational, and total disposal costs,

$$CLC = CAQ + COP + CDT \quad . \quad (8)$$

A detailed life cycle cost equation can be found by substituting the appropriate equations into Equation 8. To obtain a life cycle cost factor in terms of a cost per unit usage, the life cycle cost can be divided by the total number of operating hours yielding an item cost per system operating hour,

$$CPU = \frac{CLC}{365(NSYS)(OS)(T)} \quad . \tag{9}$$

Application of the Cost Equation

Now that a general cost equation has been developed from the defined cost elements, the support model of Example 3 can be used to show the computation of the life cycle cost, CLC, for each alternative. The data to be used for this example is tabulated in Table 1 for both the non-maintainable and reparable cases. The data presented here is not related to any existing system or item but was reasonably chosen in this application. The results of applying this data to Equations 1 through 9 are shown in Table 2. Notice from the life cycle cost that the reparable alternative appears to be the correct choice based on cost. However, variances in actual cost data may not permit such a simple comparison particularly when the difference in cost is small. Statistical methods of determining the significance of the cost difference are treated in the following section.

Table 1

COST DATA FOR EXAMPLE 3

Case Element	Reparable Value	Non-maintainable Value
CAC	$ 100.00	$ 100.00
CHCM	15.00	15.00
CD	--	--
CDOC	300.00	150.00
CEQ	600.00	300.00
CFAB	80.00	60.00
CFSN	150.00	150.00
CI	100.00	100.00
CM	125.00	100.00
CHPM	10.00	10.00
CS	10.00	--
CSP_1	.25	--
CSP_2	4.50	--
CSP_3	5.00	--
CSP_4	1.25	--
CSP_5	.25	--
CSP_6	3.00	--
CSP_7	1.75	--
$CSPI_1$	.25	--
$CSPI_2$	4.00	--
$CSPI_3$	5.50	--
$CSPI_4$	1.00	--
$CSPI_5$	.25	--
$CSPI_6$	3.00	--
$CSPI_7$	1.50	--
CST	1,000.00	1,000.00

Table 1 (continued)

CSUP	$	2,000.00	$	2,000.00
CT		10,000.00		5,000.00
CTI		8,000.00		6,000.00
MTBF	hrs	10,000.00	hrs	10,000.00
MCT		3.00		1.00
MPT		.50		.50
OS		12.00		12.00
P		3,000.00		3,000.00
T	yrs	7.00	yrs	7.00
NC	#	3	#	1
NE		50		1,000
NFAB		50		500
NI		2		2
NS		100		--
NSP_1		100		--
NSP_2		200		--
NSP_3		200		--
NSP_4		200		--
NSP_5		100		--
NSP_6		300		--
NSP_7		300		--
$NSPI_1$		100		--
$NSPI_2$		200		--
$NSPI_3$		200		--
$NSPI_4$		100		--
$NSPI_5$		100		--
$NSPI_6$		100		--
$NSPI_7$		100		--
NST		2		2
NSYS		20		20
NT		94		1,044

Table 2

RESULTS OF APPLYING DATA TO COST EQUATIONS

Equation	Case Cost	Reparable Value	Non-maintainable Value
2	CP	$ 15,000.00	$ 104,700.00
3	CPI	13,000.00	10,700.00
1	CAQ	28,000.00	115,400.00
4	CCM	2,700.00	900.00
5	CPM	525.00	525.00
6	COP	145,950.00	89,925.00
7	CDT	-1,000.00	--
8	CLC	172,950.00	205,325.00
9	CPU	$/hr 2.52	$/hr 3.34

Statistical Cost Considerations

In the preceding section, cost elements have been defined in the form of rather nebulous constants, and the resulting cost equation (Equation 8) may be viewed in general as

$$B_T = \sum_j a_j b_j \qquad (10)$$

where B_T is the total cost corresponding to CLC, the b_j's are the defined cost elements, and the a_j's are the defined non-cost multiplier quantities. If the a_j's are treated as constants, although some of these are the expected value of the system's operating parameters, no problem arises when the total cost is thought of as an item cost based on expected system operation. The fact that the cost elements are actually predicted costs also leads to the consideration of the total cost as a predicted cost.

If the accounting system or source of cost information obtains samples of cost elements from which average values are used as predictions, the accounting system can be thought of as sampling costs from the underlying distributions of the cost elements. The total cost can then be considered a random variable, C_T, equal to the linear combination of element cost variables, c_j's,

$$C_T = \sum_j a_j c_j \quad .$$

The distribution of cost element c_j might have a form as shown in Figure 8 with a mean, u_{c_j}, and a variance, $\sigma_{c_j}^2$. Then the total cost will be distributed with a mean,

$$u_{C_T} = \sum_j a_j u_{c_j} \tag{11}$$

and a variance,

$$\sigma_{C_T}^2 = {}_j a_j^2 \sigma_{c_j}^2 + 2\sum_{j<k}\sum \mathrm{Cov}(a_j\sigma_{c_j}, a_k\sigma_{c_k}) \quad . \tag{12}$$

In this paper the cost elements are assumed to be independently distributed; that is, one cost element has no influence on any of the remaining cost elements. This results in the covariance terms of Equation 12 being equated to zero, and the expression is simplified to the form

$$\sigma_{C_T}^2 = \sum_j a_j^2 \sigma_{c_j}^2 \quad . \tag{13}$$

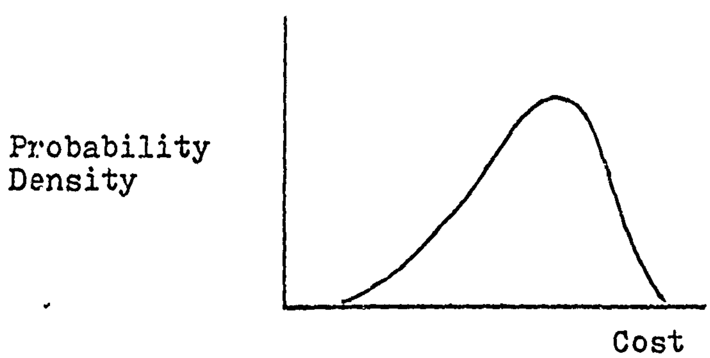

Figure 8. PROPOSED UNDERLYING COST DISTRIBUTION FOR COST ELEMENT c_j

As in Equation 10, the a_j's in Equations 11 through 13 are treated as constants although they represent such factors as repair rate and failure rate which are themselves random variables. However, the costs which have been developed were based on expected system operating parameters. To maintain this concept, only the variability of the cost elements will be considered.

Even with independently distributed cost elements, the sample costs may show correlation. It is assumed here that the methods of cost data collection provide samples which are uncorrelated. The sample mean of the total cost is a linear combination of the cost element sample means,

$$\bar{x}_{C_T} = \sum_j a_j \bar{x}_{c_j} \quad . \tag{14}$$

The sample variance of the total cost is a function of the cost element sample variances,

$$s_{C_T}^2 = \sum_j a_j^2 s_{c_j}^2 \quad . \tag{15}$$

The mean described by Equation 14 is the cost estimate usually found. In Equation 15 the cost element sample variance is calculated as

$$s_{c_j}^2 = \frac{\sum_k (x_{jk} - \bar{x}_{c_j})^2}{n_j} \tag{16}$$

where x_{jk} is the k^{th} sample value of the j^{th} cost element, and n_j is the number of sample values of the j^{th} cost

element.

The proposed distribution of cost element c_j shown in Figure 8 can be represented by the beta distribution by choosing appropriate distribution parameters. Although the cost elements do not have identical distributions because of differences in means and variances, the extension of the Central Limit Theorem by Lapunov indicates that their linear combination will have a limiting normal distribution.[4] If there are substantial numbers of costs used in finding the sample estimates, this information can be used to test the significance of the difference in expected total costs between two alternatives.

Frequently, sample values for several of the c_j's are not available and must be obtained through educated estimating. Provided that the total sample size, n_T, is still large enough to apply the Central Limit Theorem, Moder (13) has described a method of obtaining a mean, $\bar{x}_{c_j}'$, and a variance, $s_{c_j}^{2\prime}$, based on three educated estimates: a most likely cost, m; a pessimistic (high) cost, b; and an optimistic (low) cost, a. To obtain the variance, a unimodal distribution is assumed,

$$s_{c_j}^{2\prime} = (b - a)^2/36 \quad .$$

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4 For an explanation of the Theorem of Lapunov and its applications see: Marek Fisz, Probability Theory and Mathematical Statistics, 3rd ed. (New York: John Wiley & Sons, Inc., 1963), p. 202.

The mean is obtained with the additional restriction that the cost element follows a beta distribution,

$$\bar{x}_{c_j}' = (a + 4m + b)/6 \quad .$$

These can be used in the preceeding equations in place of the corresponding sample statistics.

The proposed distribution for cost element c_j as shown in Figure 8 implies a greater probability of higher costs. If the cost data has been adjusted as discussed previously, it seems likely that the underlying distribution will take on an approximately normal form as in Figure 9. By assuming a normal distribution for the c_j's, statistical tests can be used to determine the significance of the difference between two alternative costs even when the sample size does not warrant application of the Central Limit Theorem.

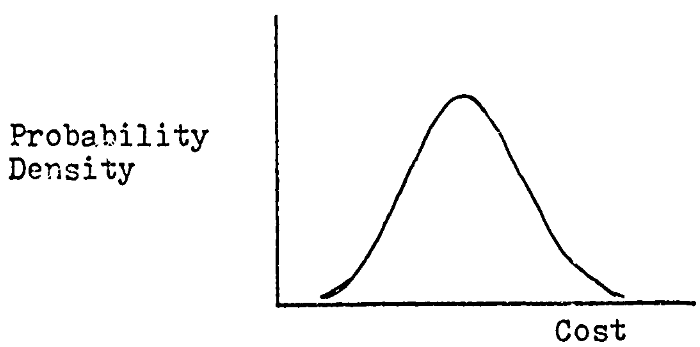

Figure 9. NORMALLY DISTRIBUTED COST ELEMENT c_j

To test whether the sample mean, $\bar{x}_{C_{T1}}$, of the total cost, C_{T1}, of one alternative is significantly greater than the sample mean, $\bar{x}_{C_{T2}}$, of a second alternative with a total cost, C_{T2}, the test of the hypothesis that the means of two normal distributions are equal can be used,

$$u_{C_{T2}} = u_{C_{T1}} \quad .$$

However, the assumption that $\sigma^2_{C_{T1}}$ is equal to $\sigma^2_{C_{T2}}$ can not usually be made. Unfortunately, an exact statistical procedure is unavailable to cover this situation. A procedure does exist based upon the test statistic t', which has the property that when C_{T1} and C_{T2} are normally distributed and $u_{C_{T1}}$ equals $u_{C_{T2}}$, t' has an approximate t distribution. The statistic t' is given by

$$t' = \frac{\bar{x}_{C_{T1}} - \bar{x}_{C_{T2}}}{\sqrt{\dfrac{s^2_{C_{T1}}}{n_{T1}} + \dfrac{s^2_{C_{T2}}}{n_{T2}}}} \tag{17}$$

and the associated degrees of freedom are

$$v = \frac{(s^2_{C_{T1}}/n_{T2} + s^2_{C_{T2}}/n_{T2})^2}{\dfrac{(s^2_{C_{T1}}/n_{T1})^2}{(n_{T1}+1)} + \dfrac{(s^2_{C_{T2}}/n_{T2})^2}{(n_{T2}+1)}} - 2 \quad . \tag{18}$$

The probability distribution of t' has not been determined when $u_{C_{T1}}$ does not equal $u_{C_{T2}}$. Hence, only one point on the operating characteristic curve can be guaranteed,

namely, + probability of accepting the hypothesis that $u_{C_{T1}}$ equals $u_{C_{T2}}$ when it is true. By computing the t' statistic in Equation 17 and finding it greater than the tabled value $t_{\alpha;v}$, where α is the level of significance of the test, the hypothesis that $u_{C_{T1}}$ is equal to $u_{C_{T2}}$ can be rejected when $u_{C_{T1}}$ is greater than $u_{C_{T2}}$. Then C_{T2} is a significantly lower cost.

An alternate approach can be followed using the F statistic to test the hypothesis that two unknown variances, $\sigma^2_{C_{T1}}$ and $\sigma^2_{C_{T2}}$, are equal. If the hypothesis is accepted, an exact t statistic is used to test the hypothesis that $u_{C_{T1}}$ and $u_{C_{T2}}$ are equal. The t statistic is given by

$$t = \frac{\bar{x}_{C_{T1}} - \bar{x}_{C_{T2}}}{\sqrt{\frac{1}{n_{T1}} + \frac{1}{n_{T2}}}\ \sqrt{\frac{n_{T1} s^2_{C_{T1}} + n_{T2} s^2_{C_{T2}}}{n_{T1} + n_{T2} - 2}}} \quad . \qquad (19)$$

By computing the t statistic in Equation 19 and finding it greater than the tabled value, $t_{\alpha;n_{T1}+n_{T2}-2}$, the hypothesis that $u_{C_{T1}}$ is equal to $u_{C_{T2}}$ can be rejected when $u_{C_{T1}}$ is greater than $u_{C_{T2}}$. Then C_{T2} is a significantly lower cost.

CHAPTER V

SUMMARY AND CONCLUSIONS

The factors influencing the repair policy decision have been investigated. While cost usually assumes the dominant role in the decision process, the proposed support concepts, system operational characteristics, and system deployment requirements must be carefully examined to first determine the feasibility of the alternatives. In cases where the cost difference between some alternatives are not large enough to be the deciding factor, the particular characteristics of the repair policy may help determine which alternative is most appropriate.

Considering a complex system as a whole, it is obvious that neither completely reparable designs nor completely non-maintainable designs are valid solutions to the problem. A complex system will be characterized by a combination of these two designs and their corresponding repair policies. Therefore, the repair policy decisions are made at lower structural levels in the system, and it is at these points that cost modeling techniques must be applied.

In this paper, it has been assumed that a proposed system is in the design and development phase, that a functional system design has been accomplished, and that an allocation procedure has provided quantitative design

requirements for the functional blocks. To meet these requirements several designs with their corresponding repair policies are proposed. For a cost-based decision, the technique used in this paper develops a support model from which operational costs peculiar to each repair policy can be identified and incorporated into a cost equation. The cost equation simply enumerates the costs pertaining to an alternative over the life cycle of the system. These enumerated costs are called cost elements. They have been defined in such a way that the acquisition cost can be determined as an allocated system cost; the elements comprising the operational cost are defined according to category to be obtainable from present military accounting systems.

While little danger exists in a cost-based decision which chooses the least-cost alternative when there is a large difference in life cycle costs, the same cannot be said when the differences are not so large. The reason lies in the predictive nature of the costs used. For the most part these are educated estimates or time averaged data biased by inflationary trends, resulting in large differences between prediction and fact. Until the various military agencies and contractors systematize the collection of data and adopt uniform techniques to transform the raw data to useful unbiased cost elements, any technique

of cost estimating will provide nothing better than gross estimates. Methods to standardize, collect, and transform raw cost data are recommended for future research in this area.

The section of this report on statistical condiderations introduces methods which might be of use in determining the significance of life cycle cost differences by statistical means. It is assumed here that sufficient data exists to obtain estimates of the variances of the cost elements and to warrant application of the Central Limit Theorem. The cost elements are also considered independently distributed..This paper leaves room for further development of these statistical techniques as they are not usually applicable with current cost data.

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